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AN INVESTIGATION AND ANALYSIS OF SURFACE ROUGHNESS AND TOOL WEAR IN DRY POCKET MILLING OF ALUMINUM ALLOY AL7075

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ABSTRACT

This study was conducted to investigate the influence of milling parameters and machining time on the surface roughness and tool wear. The experimental was designed and conducted with three controllable factors-three levels (axial depth of cut, feed rate, and cutting speed) in dry pocket milling processes of aluminum alloy Al7075. Performance measurements that were chosen to perform were surface roughness and tool wear at three machining time (after 90 minutes machining, after 180 minutes machining, and after 270 minutes machining). The effect of cutting conditions on the surface roughness and tool wear were analyzed and evaluated. In almost cases, the most significant factor that influnced on the surface roughness and tool wear as well was feed rate (from 54.78% to 62.27 % for roughness surface and from 70.71 to 87.15 % for tool wear). Linear regression that was determined as the most suitable regression of tool wear and surface roughness with the determination coefficients (R^2) from 95.12 % to 96.14 % for tool wear, and from 91.27 % to 96.18 % for surface roughness. These regression models were successfully verified by comparison of predicted and measured results of tool wear and surface roughness. Besides, the influence of the machining time on the surface roughness and tool wear was also investigated with the interesting results. Moreover, the relationship between surface roughness and tool wear was also analyzed. Tool wear, surface roughness models, and their relationship can be used to improve the surface quality and the tool life in dry pocket milling the aluminum alloy Al7075.

KEYWORDS: Surface Roughness, Tool Wear, Machining Parameter, ANOVA & Al7075

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Original Article

1. INTRODUCTION

As evident in history, an important aspect of manufacturing is machining, which removes unwanted material to produce size, shape and smooth surface for performance. In the machining processes, milling is one of the most important processes in manufacturing industry. In the milling process, a reliable quantitative prediction of surface roughness and tool wear is very important to predict the surface quality, geometrical accuracy, tool life, etc.

In recent years, many studies were performed to investigate the influence of cutting conditions on the tool wear and finished surface roughness to improve the quality and reduce the cost of machining processes. The study focused in the different machining processes such as milling [1-3], turning [4-6], drilling [7], and so on. In milling processes, the studies about tool wear and surface roughness that was conducted following two directions. In the first direction, the tool wear and surface roughness were modeled depending on the physical, chemical, and geometrical phenomena such as friction, temperature, cutting, etc [8, 9]. This approach is quite difficult to perform because many factors that affect on the tool wear and surface roughness. In the second direction, the tool wear and

surface roughness were modeled depending on the experimental data. This approach can be applied for specific cases in which only several factors were considered in the investigation of their influence on the tool wear and surface roughness [10-12].

In the experimental modelling method, several approaches were applied to model the tool wear and surface roughness depending on the cutting time or cutting conditions. The tool wear and surface roughness were investigated in milling process depending on the cutting time. This study was carried out to verify the change in surface roughness of the workpiece due to increasing tool wear. [13, 14]. The neural approach was applied to investigate the influence of cutting condition of tool wear and average surface roughness in turning process under minimum quantity lubrication (MQL) environment. [15]. The influence of the cutting conditions on the tool wear and the surface finish criteria have been determined through the response surface methodology (RSM) prediction model. The prediction models of tool wear and surface roughness are also used to determine the combined effect of machining parameters on the tool wear and surface roughness [12, 16].Taguchi experimental design was used to investigate the influence of cutting conditions on tool wear and surface roughness and to obtain the optimum cutting parameters in minimizing surface roughness while turning hardened AISI 4140. By using the L9 orthogonal array, the experiments were conducted in a CNC machine to investigate the effects of cutting parameters on surface roughness by applying statistical methods of signal to noise ratio (SNR) and ANOVA [17]. Taguchi technique was also used to investigate the influences of machining parameters on surface roughness, tool wear. The analysis of the result revealed that the combination of high cutting speed and low feed rate is important for minimizing the surface roughness [18]. In the milling of nickel-based Waspaloy with ceramic tools, the investigation of influence of cutting parameters and cooling conditions on tool wear and surface roughness was evaluated. By using the multi objective optimization method, the minimum quantity lubrication method was the best cooling method in determination of minimum values of tool wear and surface roughness [19].

Aluminium alloys as engineering materials that have been playing an important role in every sector of the industry, due to its low density, high machinability. These alloys are used extensively in automotive, aerospace, marine and architectural applications because of their high specific strength and corrosion resistance [20]. However, machining of Al and its alloy and finding the suitable tool is really a big challenge because of its formation of BUE (Built-up Edge) and BUL (Built-up Layer), and the chips stick to the tool in the machining processes [20].There are many studies that were performed to investigate the influence of cutting conditions on surface roughness and determine the optimum values of machining parameters. However, the studies about tool wear and surface roughness when machining the aluminum or aluminum alloy have not been mentioned. The influence of machining time on the tool wear and surface roughness, and the relationship between tool wear and surface roughness were also rarely mentioned.

This study was conducted to investigate the effect of milling parameters and machining time on the surface roughness and tool wear when dry pocket milling the aluminum alloy Al7075. So, the effect of cutting conditions on surface roughness and tool wear was evaluated. The tendency of surface roughness and tool wear depending the machining time was determined, and the relationship between surface roughness and tool wear was also investigated.

2. EXPERIMENTAL METHOD

2.1. The setup of experiment method

2.1.1. Cutter and Workpiece

The cutter was a flat-end mill HSSCo8 Cutter, with number of flutes N = 2. The tool diameter is 6 mm. The cutting edge effective length is 15 mm. The cutting part of tool was coated by TiN to obtain the too hardness of 60 HRC.

The workpiece material was Aluminum alloy Al7075 that has the properties: Hardness of 60 HB, Young's modulus of 70 - 80 GPa, Density of 2.7 g/cm3. The dimensions of workpiece are 300 mm × 150 mm × 20 mm as shown in Fig. 1. The workpiece material compositions are listed in **Table 1**.

Figure 1: Experimental Workpieces.

Table 1: Chemical Composites of Aluminum Alloy Al7075

Element	Cu	Mn	Mg	Cr	Zn	Ti	Al
Composite (%)	1,2-2,0	0,3	2,1-2,9	0,18-0,28	5,1-6,1	0,2	remainder

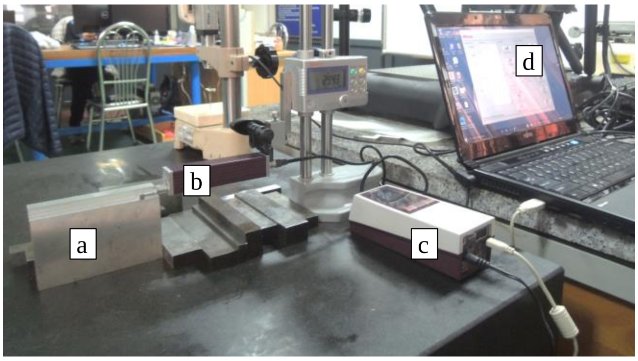
2.1.2. Machine Set-up

The experiments were performed at a three-axis vertical machining center (HS Super MC500) as described in **Figure2**. The spindle speed is in range 100 ÷ 30000 rpm, the maximum feed rate is 48000 mm/min. All experiments were peformed under dry machining condition.

Figure 2: Experimental Machine.

2.1.3. Surface Roughness Measurement System

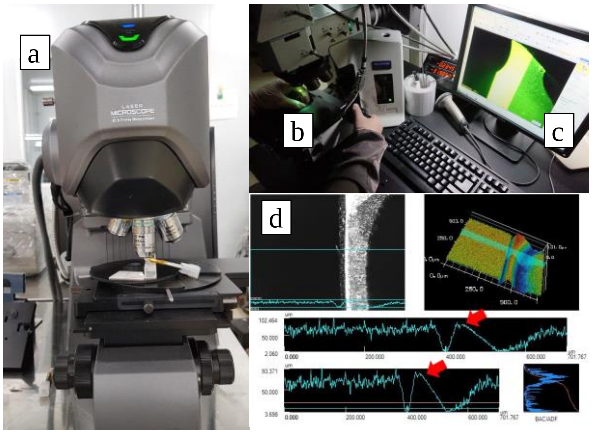
The surface roughness (R_a) of the product was measured by MITUTOYO-Surftest SJ-210 Portable Surface Roughness Tester **(**Japan**)** as described in **Figure 3**. The cut-off length and evaluation length were fixed at 0.8 mm and 4 mm, respectively. The surface roughness was measured parallel to the machined surface from three different points and repeated three times following three repeated times of each cutting test. The average values of the measurements were evaluated.



a. Workpiece b. Tool tip c. Data processing device d. PC and software
Figure 3: Setting of Surface Roughness Measurement.

2.1.4. Tool Wear Measurement System

The flank wear of tool (VB) of the product was measured by Color 3D Laser Microscope Color 3D Laser Microscope VK-X100K/X200 Series system **(**U.S.A**)** as shown in **Figure 4**. The values of tool wear were measured at three machining time (after 90 minutes, after 180 minutes, and after 270 minutes).



a. 3D Laser Microscope b. Tool
c. Data processing system d. The measured results
Figure 4: Setting of Tool Wear Measurement.

2.2. Experimental design

In this research, the axial depth of cut (a), feed rate (F), and the cutting speed (V_c) were selected as control factors and their levels were expressed in the Table 2. In the experimental layout plan, with three factors and three levels, the experimental plan was performed with 11 experiments at three machining time (after 90 minutes, after 180 minutes, and after 270 minutes) to analyze the influence of machining parameters on the surface roughness and tool wear. The experimental design was detailed as in Table 3. Besides, the response surface methodology (RSM) technique has been used for design of experiments and analysis of experimental results. The relationship between one or more response variable and essential controllable input variables [22].

Table 2: Milling Parameters and their Levels

No.	Machining parameters	Level 1	Level 2	Level 3
1	Axial depth of cut, a (mm)	0.5	1.0	1.5
2	Feed rate, F (mm/flute)	800	1200	1600
3	Cutting speed, V_c (m/min)	188	282	376

Table 3: The Experimental Design and Results

Time (minute)	No.	Code factors			Machining parameter			Performance measures	
		X1	X2	X3	a (mm)	F (mm/min)	V (m/min)	Ra (µm)	VB (µm)
90	1	-1	-1	-1	0.5	800	188	0.854	12.523
	2	1	-1	-1	1.5	800	188	0.934	14.353
	3	-1	1	-1	0.5	1600	188	0.961	16.433
	4	1	1	-1	1.5	1600	188	1.015	17.867
	5	-1	-1	1	0.5	800	376	0.870	11.510
	6	1	-1	1	1.5	800	376	0.877	14.227
	7	-1	1	1	0.5	1600	376	0.921	15.327
	8	1	1	1	1.5	1600	376	0.933	15.593
	9	0	0	0	1.0	1200	282	0.908	14.235
	10	0	0	0	1.0	1200	282	0.908	14.597
	11	0	0	0	1.0	1200	282	0.923	14.530
180	1	-1	-1	-1	0.5	800	188	0.173	20.122
	2	1	-1	-1	1.5	800	188	0.253	23.445
	3	-1	1	-1	0.5	1600	188	0.280	28.401
	4	1	1	-1	1.5	1600	188	0.333	30.514
	5	-1	-1	1	0.5	800	376	0.188	18.210
	6	1	-1	1	1.5	800	376	0.195	24.188
	7	-1	1	1	0.5	1600	376	0.239	25.020
	8	1	1	1	1.5	1600	376	0.252	27.386
	9	0	0	0	1.0	1200	282	0.226	22.395
	10	0	0	0	1.0	1200	282	0.227	23.334
	11	0	0	0	1.0	1200	282	0.242	22.927
270	1	-1	-1	-1	0.5	800	188	0.912	50.577
	2	1	-1	-1	1.5	800	188	0.992	63.640
	3	-1	1	-1	0.5	1600	188	1.019	87.873
	4	1	1	-1	1.5	1600	188	1.073	91.813
	5	-1	-1	1	0.5	800	376	0.928	53.523
	6	1	-1	1	1.5	800	376	0.935	61.550
	7	-1	1	1	0.5	1600	376	0.979	77.533
	8	1	1	1	1.5	1600	376	0.991	80.287
	9	0	0	0	1.0	1200	282	0.966	73.087
	10	0	0	0	1.0	1200	282	0.966	72.177
	11	0	0	0	1.0	1200	282	0.981	72.680

3. EXPERIMENTAL RESULTS AND DISCUSIONS

3.1. Analysis for Surface Roughness

3.1.1. Analysis of Variance (ANOVA) for Surface Roughness

The experimental results were investigated and listed in **Table 3**. In this study, ANOVA was used to analyze the influence of axial depth of cut, feed rate, and cutting speed on the surface roughness and tool wear. This analysis was performed with 95% confidence level and 5% significance level. This indicates that the obtained models are considered to be statistically significant. The determination coefficient (R^2) is defined as the ratio of the explained variation to the total variation and is a measure of the fit degree.

Table 4: Results of ANOVA for Surface Roughness

ANOVA for Surface Roughness after 90 Minutes Machining						
Number of obs:	**11**		**R-squared:0.9823**			
Root MSE:	**0.007132**		**Adj R-squared:0.9705**			
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob> F**	**Percent contribution (%)**
Model	0.016951	4	0.004238	83.32	0	
a [mm]	0.004942	2	0.002471	48.58	0.0002	28.64
F [mm/phut]	0.009453	1	0.009453	185.86	0	54.78
Vc (m/phut)	0.002556	1	0.002556	50.26	0.0004	14.81
Error	0.000305	6	5.09E-05			1.77
Total	0.017256	10	0.001726			100.00
ANOVA for surface roughness after 180 minutes machining						
Number of obs:	**11**		**R-squared:0.9996**			
Root MSE:	**0.010138**		**Adj R-squared:0.9944**			
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob> F**	**Percent contribution (%)**
Model	0.018674	4	0.004669	45.42	0.0001	
a [mm]	0.003849	2	0.001925	18.73	0.0026	19.95
F [mm/phut]	0.012013	1	0.012013	116.88	0	62.27
Vc (m/phut)	0.002813	1	0.002813	27.36	0.002	14.58
Error	0.000617	6	0.000103			3.20
Total	0.019291	10	0.001929			100.00
ANOVA for surface roughness after 270 minutes machining						
Number of obs:	**11**		**R-squared:0.9996**			
Root MSE:	**0.010541**		**Adj R-squared:0.9944**			
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob> F**	**Percent contribution (%)**
Model	0.017788	4	0.004447	40.02	0.0002	
a [mm]	0.002488	2	0.001244	11.2	0.0094	13.48
F [mm/phut]	0.01125	1	0.01125	101.25	0.0001	60.96
Vc (m/phut)	0.00405	1	0.00405	36.45	0.0009	21.95
Error	0.000667	6	0.000111			3.61
Total	0.018455	10	0.001845			100.00

The ANOVA results for surface roughness were illustrated in **Table 4** in which the contributions of each factor on amplitude of feed force were listed in the last column. According to **Table 4**, the contributions of each factor on surface roughness were listed in the last column. It is clear from the results of ANOVA that the most important factor affecting on the surface roughness was feed rate in all machining time (54.78 % after 90 minutes machining, 62.27 % after 180 minutes machining, and 60.96 % after 270 minutes machining). The other factors affect differently on the surface roughness. In almost machining time, the second factor influencing on the surface roughness was axial depth of cut (28.64 % after 90

minutes machining, 19.95 % after 180 minutes machining). In almost machining time, the third factor influencing on the surface roughness was cutting speed (14.81 % after 90 minutes machining, 14.58 % after 180 minutes machining).

3.1.2. Regression and Verification of surface roughness model

The regression analysis was used to model and analyze the relationship between a dependent variable and one or more independent variables. In this paper, three dependent variables are surface roughness and tool wear, whereas the independent variables are axial depth of cut (a), feed rate (F), and cutting speed (V_c). In this section, by using Intercooled Stata 8.2^{TM} software, the most suitable regression of surface roughness was a linear regression as given in **Eq. 1 to Eq.3**. The R^2 values of the equations obtained by linear regression model for surface roughness were found to be from 91.27 % to 96.18 %.

After 90 minutes machining

$$\begin{cases} Ra(90) = 0.8339773 + 0.04325 * a + 0.0000859 * F - 0.0001902 * Vc \\ R^2 = 91.27\%, \quad R^2_{Ajd} = 87.53\% \end{cases} \quad (1)$$

After 180 minutes machining

$$\begin{cases} Ra(180) = 0.1384091 + 0.0425 * a + 0.0000969 * F - 0.0001995 * Vc \\ R^2 = 95.58\%, \quad R^2_{Ajd} = 93.68\% \end{cases} \quad (2)$$

After 270 minutes machining

$$\begin{cases} Ra(270) = 0.8963637 + 0.35 * a + 0.0000937 * F - 0.0002394 * Vc \\ R^2 = 96.18\%, \quad R^2_{Ajd} = 94.55\% \end{cases} \quad (3)$$

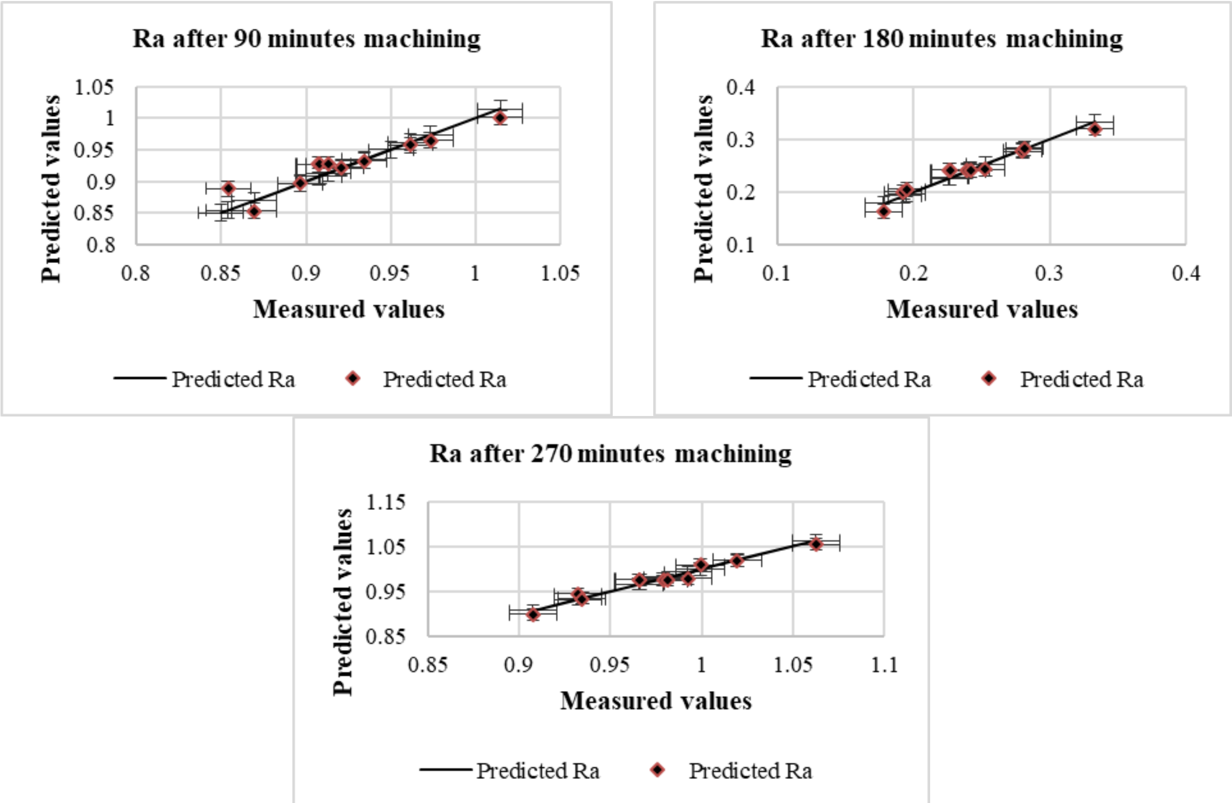


Figure 5: Measured and Predicted Results of Surface Roughness.

The verification results of surface roughness model were described in **Figure 5**. As seen from these figures, in almost machining time (after 90 minutes machining, after 180 minutes machining, and after 270 minutes machining), the predicted results were very close to the experimental results. There is a very good relation between predicted values and test values. These results showed that the linear regression model was shown to be successfully investigated of surface roughness in pocket milling processes of aluminum alloy Al7075.

3.2. Analysis for Tool Wear

3.2.1. Analysis of Variance (ANOVA) for Tool Wear

The ANOVA results for tool wear were illustrated in **Table 5. T**he contributions of each factor on the tool wear were listed in the last column. In machining time, the most important factor affecting on the tool wear was feed rate (70.71 % after 90 minutes machining, 72.89 % after 180 minutes machining, and 87.15 % after 270 minutes machining). The second factor influencing on the tool wear was axial depth of cut (17.49 % after 90 minutes machining, 15.93 % after 180 minutes machining, and 7.19 % after 270 minutes machining). The third factor influencing on the tool wear was cutting speed (7.56 % after 90 minutes machining, 9.12 % after 180 minutes machining, and 2.00 % after 270 minutes machining).

Table 5: Results of ANOVA for Tool Wear

ANOVA for tool wear after 90 minutes machining						
Number of obs:	**11**		**R-squared:0.9996**			
Root MSE:	**0.466793**		**Adj R-squared:0.9944**			
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob > F**	**Percent contribution (%)**
Model	29.52683	4	7.381708	33.88	0.0003	
a [mm]	5.392005	2	2.696002	12.37	0.0074	17.49
F [mm/phut]	21.80311	1	21.80311	100.06	0.0001	70.71
Vc (m/phut)	2.331704	1	2.331704	10.7	0.017	7.56
Error	1.307372	6	0.217895			4.24
Total	30.83419	10	3.083419			100.00
ANOVA for tool wear after 180 minutes machining						
Number of obs:	**11**		**R-squared:0.9996**			
Root MSE:	**0.663656**		**Adj R-squared:0.9944**			
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob > F**	**Percent contribution (%)**
Model	125.6984	4	31.42459	71.35	0	
a [mm]	20.44655	2	10.22328	23.21	0.0015	15.93
F [mm/phut]	93.54385	1	93.54385	212.39	0	72.89
Vc (m/phut)	11.70796	1	11.70796	26.58	0.0021	9.12
Error	2.642633	6	0.440439			2.06
Total	128.341	10	12.8341			100.00
ANOVA for tool wear after 270 minutes machining						
Number of obs:	**11**		**R-squared:0.9996**			
Root MSE:	**3.31811**		**Adj R-squared:0.9944**			
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob > F**	**Percent contribution (%)**
Model	1740.178	4	435.0446	39.51	0.0002	
a [mm]	129.9567	2	64.97833	5.9	0.0383	7.19
F [mm/phut]	1574.054	1	1574.054	142.97	0	87.15
Vc (m/phut)	36.16754	1	36.16754	3.29	0.1199	2.00
Error	66.05932	6	11.00989			3.66
Total	1806.238	10	180.6238			100.00

3.2.2. Regression and Verification of Tool Wear Models

The most suitable regression of tool wear was a linear regression as given in **Eq. 4 to Eq. 6**. The R^2 values of the equations obtained by linear regression model for tool wear were found to be from 95.12 % to 96.14 %. The compared results of measured values and predicted values of tool wear were described in **Figure 6**. It seems that the predicted results were very close to the measured results. These results showed that the linear regression models were shown to be successfully investigated of tool wear in pocket milling processes of aluminum alloy Al7075.

After 90 minutes machining

$$\begin{cases} VB(90) = 9.727522 + 1.61175 * a + 0.0041272 * F - 0.0057434 * Vc \\ R^2 = 95.12\%, \quad R^2_{Ajd} = 93.03\% \end{cases} \tag{4}$$

After 180 minutes machining

$$\begin{cases} VB(180) = 14.51139 + 2.945 * a + 0.0085488 * F - 0.0128697 * Vc \\ R^2 = 95.53\%, \quad R^2_{Ajd} = 93.61\% \end{cases} \tag{5}$$

After 270 minutes machining

$$\begin{cases} VB(270) = 28.05538 + 7.946002 * a + 0.0350675 * F - 0.0226197 * Vc \\ R^2 = 96.14\%, \quad R^2_{Ajd} = 94.48\% \end{cases} \tag{6}$$

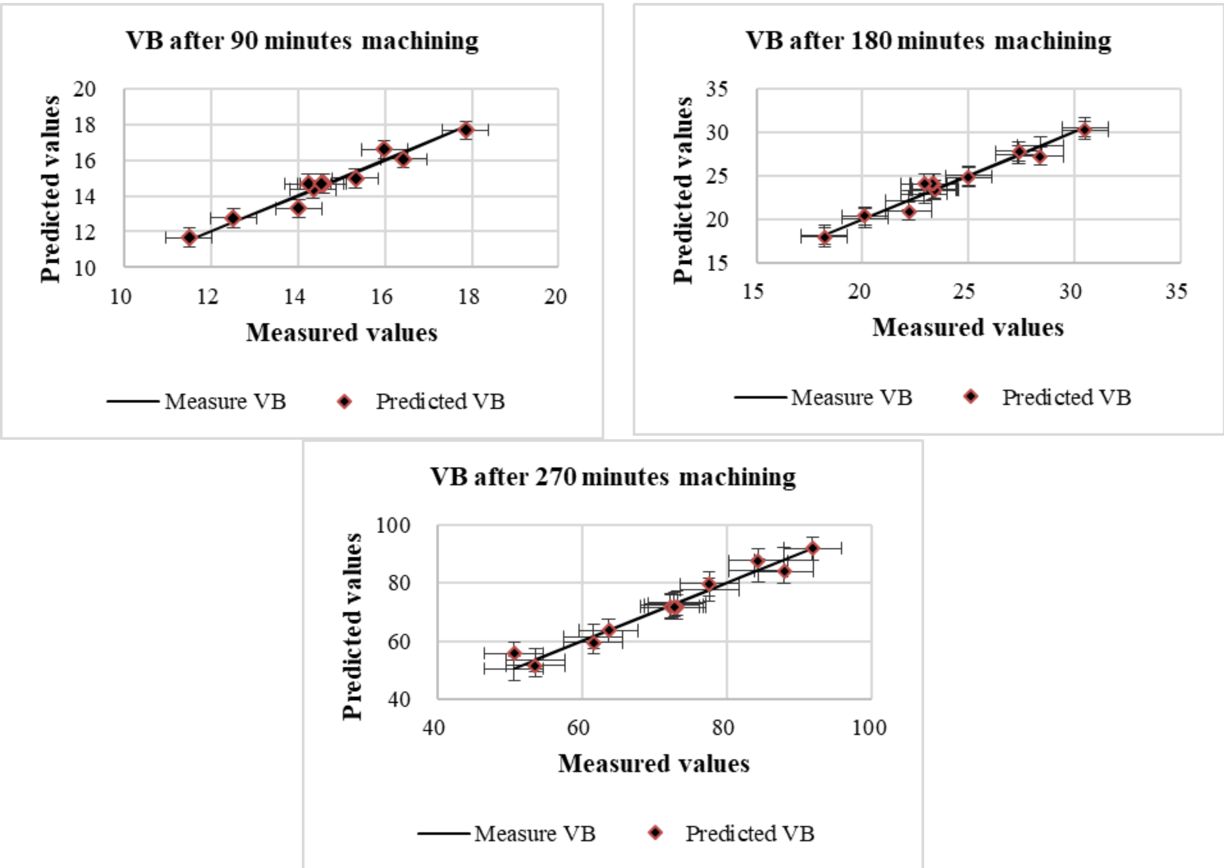


Figure 6: Measured and Predicted Results of Tool Wear after 90 Minutes Machining.

3.3. The Changes of Tool Wear and Surface Roughness depending the Milling time

The change of the surface roughness depending on the machining time was investigate and described as in **Figure 7**. It seems that the tendency of the surface roughness for all experiments was the same at all samping time. As seen from this figure, in the begining of cutting process, the values of surface roughness were quite large, after that, the surface roughness decresed, after a machining period, the tendency of surface roughness increased depending on the machining time. hese can be explained that at the beginning time of the machining process, the new tool that was used has many sharp edges, in machining, the sharp edges will scratch the workpiece surface making the surface roughness of great value. After begining time of the machining, due to the abrasion of the edges, these sharp edges do not scratch on the workpiece surface, making the surface roughness tend to decrease. After a period of machining time, due to the increasing of the tool wear, the geometry of the cutting tool changes more strongly, which makes the surface roughness tend to increase.

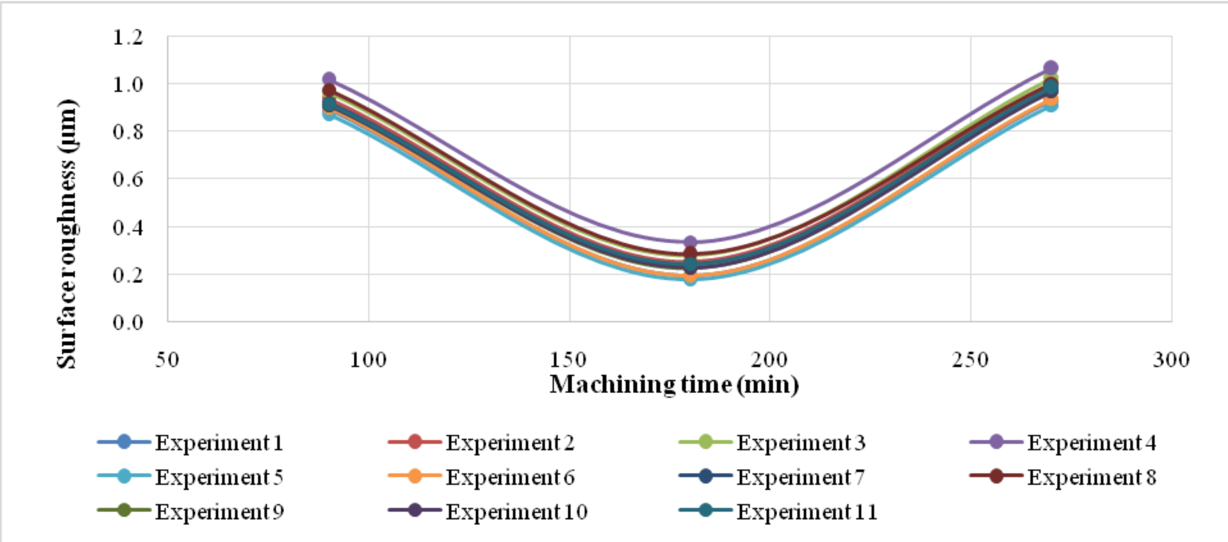


Figure 7: Surface Roughness vs. Machining Time.

The change of the tool wear depending on the machining time was described as in **Figure 8**. As seen from this figure, in the begining of cutting process, the values of tool wear increased more strongly, after that, the tool wear also incresed but these changes were quite small, after a machining period, the tendency of tool wear continue to increase more strongly depending on the machining time. These can be explained that at the beginning time of the machining process, the new tool that was used has many sharp edges, in machining, the sharp edges will scratch the workpiece surface, making the tool wear increased more strongly. After a begining period time of machining, due to the abrasion of the edges, these sharp edges do not scratch on the workpiece surface, making the tool wear tend to increase but these changes were quite mall. After a period of machining time, due to the increase of the machining temparature, the tool wear also increases more strongly, which makes the surface roughness tend to increase.

As seen from these figures and analyzed results, in pocket milling process, tool wear and surface roughness changed depending on the changes of the machining time. At the abrasion stable condition (tool wear changed small), the surface roughness was also quite small. So, in the milling processes, in order to creating the finished surface, the tool at the abrasion stable condition that can be used to improve the quality of milling processes.

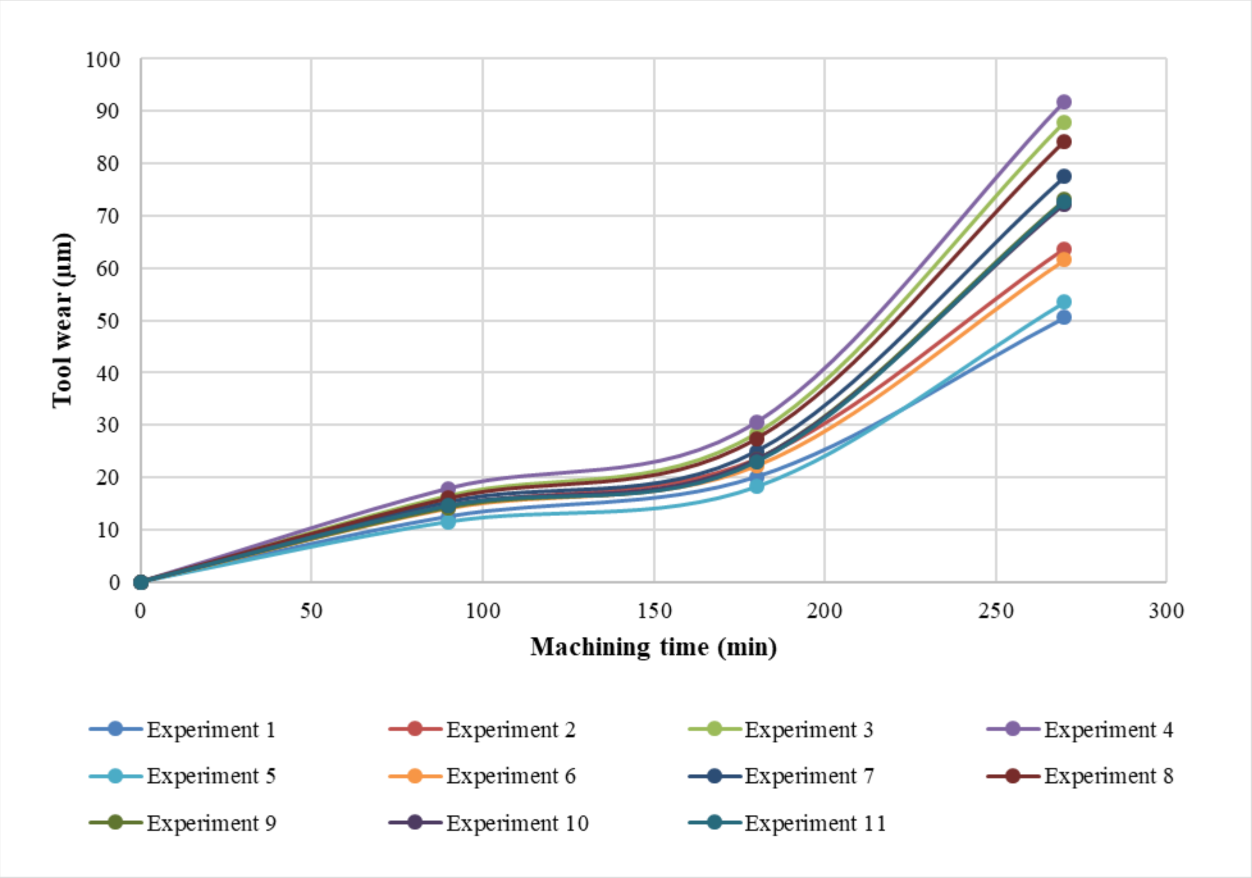


Figure 8: Tool Wear vs. Machining Time.

3.4. The Relationship between Tool Wear and Surface Roughness in Milling

In this paper, the relationship between tool wear and surface roughness was also investigated and drawn in one diagram as shown in **Figure 9.** It seems that the tendency of the surface roughness is the same that one of tool wear in machining time. As seen from this figure, in machining time, if the tool wear increased, the surface roughness increased and if the tool wear decreased, the surface roughness also decreased. These can be explained that in machining process, when the tool wear changes, the geometry of the cutting tool also changes, and then, the surface roughness also will be changed.

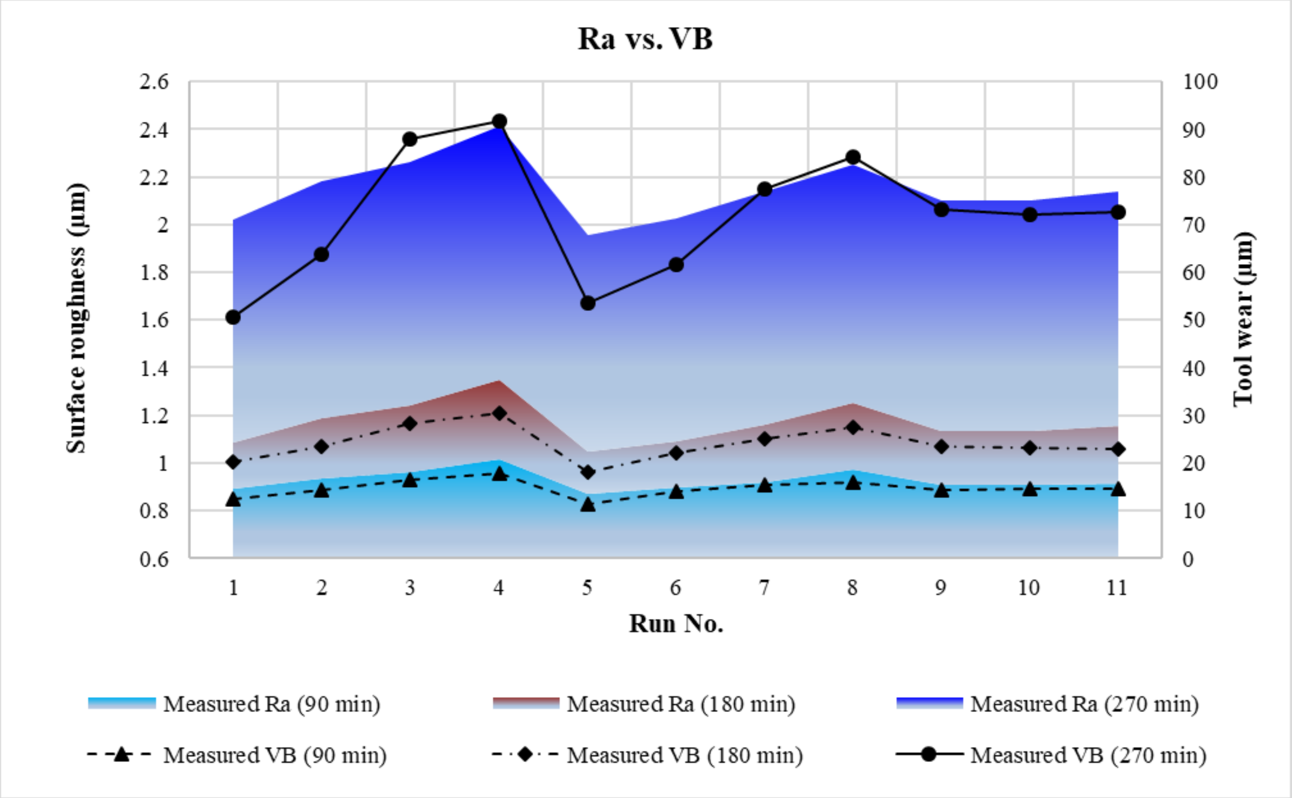


Figure 9: Relationship between Tool Wear and Surface Roughness.

4. CONCLUSIONS

An experimental method was performed to investigate the influence of cutting conditions and machining time on the surface roughness and tool wear. Depending on the analysis of experimental results, the conclusions of this study can be drawn as follows:

- The most important factor affecting on the tool wear and surface roughness was feed rate, while the second factor influencing on the tool wear and surface roughness was axial depth of cut, and the third factor influencing on the surface roughness and tool wear was cutting speed.
- The most suitable regression of tool wear and surface roughness was a linear regression. The R2 values of the equations obtained by linear regression model were found to be from 95.12 % to 96.14 % for tool wear, and from 91.27 % to 96.18 % for surface roughness. All regression models were successfully verified by experimental results with very promising results.
- The tool wear and surface roughness changed depending on the change of the machining time. At the abrasion stable condition (tool wear changed small), the surface roughness was also quite small.
- In almost machining time, if the tool wear increased, the surface roughness increased and if the tool wear decreased, the surface roughness also decreased.

The tool wear, surface roughness models, and their relationship can be applied in the adaptive control processes of CNC milling to improve the machining surface and reduce the tool life, and will be the futuristic study of the extended research.

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